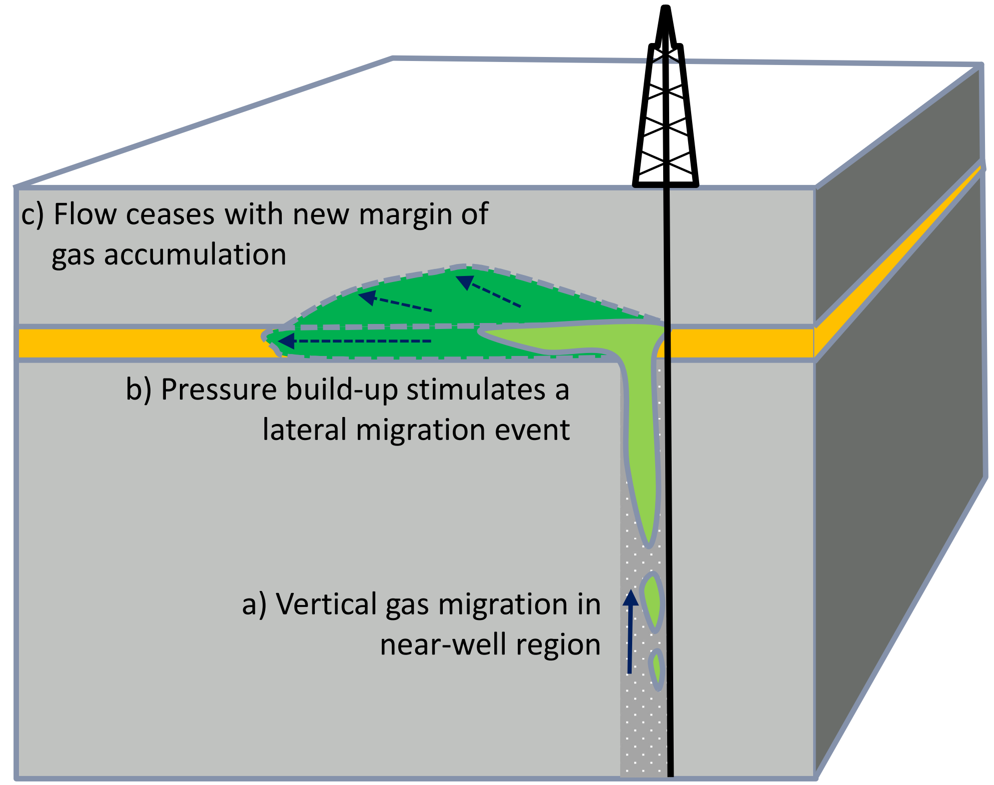
Sequential multi-physics models of gas/CO_2 migration along well paths, faults and fractures

Or why migrating CO_2 faces a lot of resistance

Philip Ringrose, NTNU, Trondheim, Norway

with a lot of help from my colleagues



Reconstruction of gas migration event at 492m depth following the 1989 underground blow out

FORCE CCS Legacy Wells Seminar, 19-20 Nov 2026 Stavanger

CGF SFI Centre for Geophysical Forecasting

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A little bit of exploration history

HP/HT wildcat well 2/4-14

1. On **6th October 1988**, wildcat well 2/4-14 was drilled by operator Saga Petroleum ASA on the Steinbit Terrace, Central Graben (TD at 4734 m in the Late Jurassic Tyne Group)
2. Following a stuck drill-string, a technical sidetrack was drilled and the mud weight was increased to near the fracture gradient.
3. At 4734 m the well experienced a gas kick, and several attempts were made to gain control, without success.
4. After a coiled tubing was run (also problematic) the well then developed into an **underground blow out** on **20th January 1989** (when the cement plug failed).
5. Subsequent PLT and 'noise' logs indicated the reservoir fluid had breached the casing and was likely charging shallower sandstone beds.
6. Repeated **shallow seismic data** confirmed that an underground blow-out was in progress and was charging sandstone beds at 828-878m depth.
7. A new safety plug and 'no-go cap' were installed in the BOP
8. A relief well (2/4-15S) was then drilled to assist in well-kill operations.
9. The 2/4-14 well was finally killed by the relief well on **12th December 1989.**
10. **Here endeth the story!**
11. Not quite yet….

Treasure Saga drilling rig
Norsk Oljemuseum Archive

Sources: Jones et al. 2013 and https://factpages.sodir.no/

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Series two … and three (no intended connection to Netflix)

A. In August 2016, the *Treasure Saga* Semi-submersible drilling rig, renamed as *Transocean Winner,* ran aground on coast of the Isle of Lewis in Scotland as it was being towed to Malta

B. In October 2018, AkerBP acquired the operatorship of the King Lear discovery from Equinor with plans to develop it as a satellite to Ula.

C. In 2019, Martin Landrø and colleagues published a <u>reconstruction of the gas flows</u> through the shallow overburden sediments using passive and active seismic field data
International Journal of Greenhouse Gas Control

The Guardian, 15th August 2016**:**
"Salvage crew boards stricken Transocean Winner oil platform"
Photograph: Andrew Milligan/PA

Reconstruction of an historic gas blow-out (overburden flow)

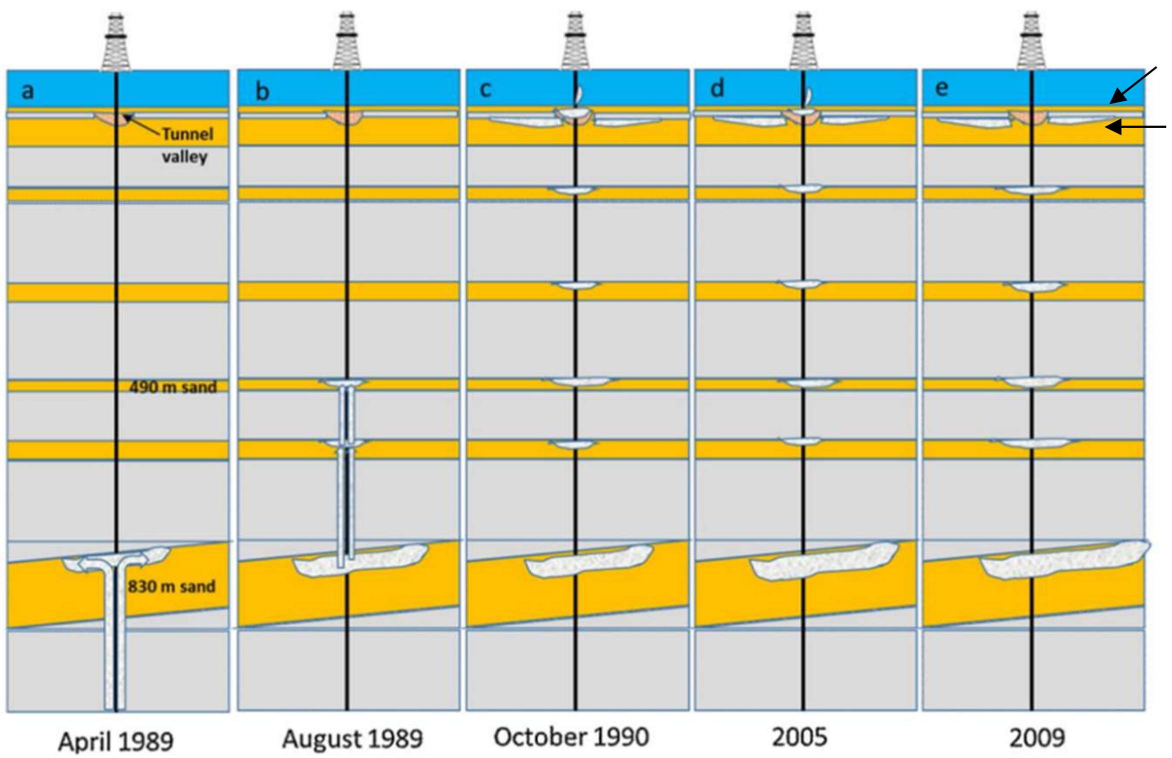
- Landrø et al. (2019) published a reconstruction of a series of gas migration events using time-lapse seismic data
- Origin of gas was a hydrocarbon exploration well blowout from a 4700m-deep interval in the North Sea in 1989.

Application to shallow gas migration case study

Glacial sands

490m

830m



Fraction of gas that migrated to shallower levels (1989 to 2009)

Below detection limit

Close to zero but detected

0.017 %

9.1 %

Using estimated column heights, we can calculate fluid and threshold pressures for migration events:

- 830m sand had a P_{max} of 1.87 MPa - implying that a shale with a permeability of ~0.6 microdarcy was breached.
- Effective vertical permeability of the wellbore damage zone must have been < 0.25 mD (Callioli Santi et al. 2022)

Note that nearly all the deep gas blow-out volume (<370Mm^3) was retained in the overburden, with <15m^3 making it all the way to the seabed

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Reconstruction of an historic gas blow-out (overburden flow)

Interpretation of the gas migration event (U-type passive seismic event):

- Left: Apparent velocity of the microseismic events was used to infer the vertical and lateral flow parts of the gas migration event which lasted for 40 minutes
- Right: Seismic amplitude map of the gas-charged layer at 492 m, with the sector of passive seismic event recordings

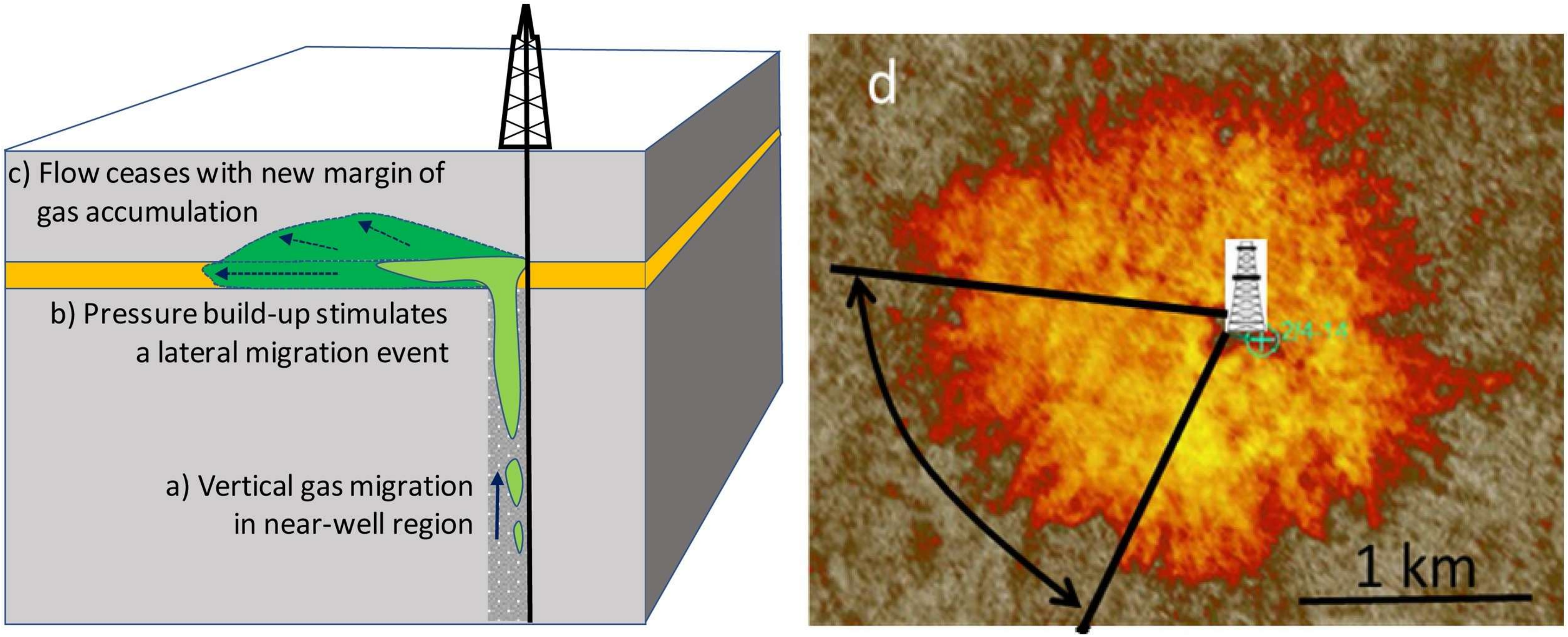
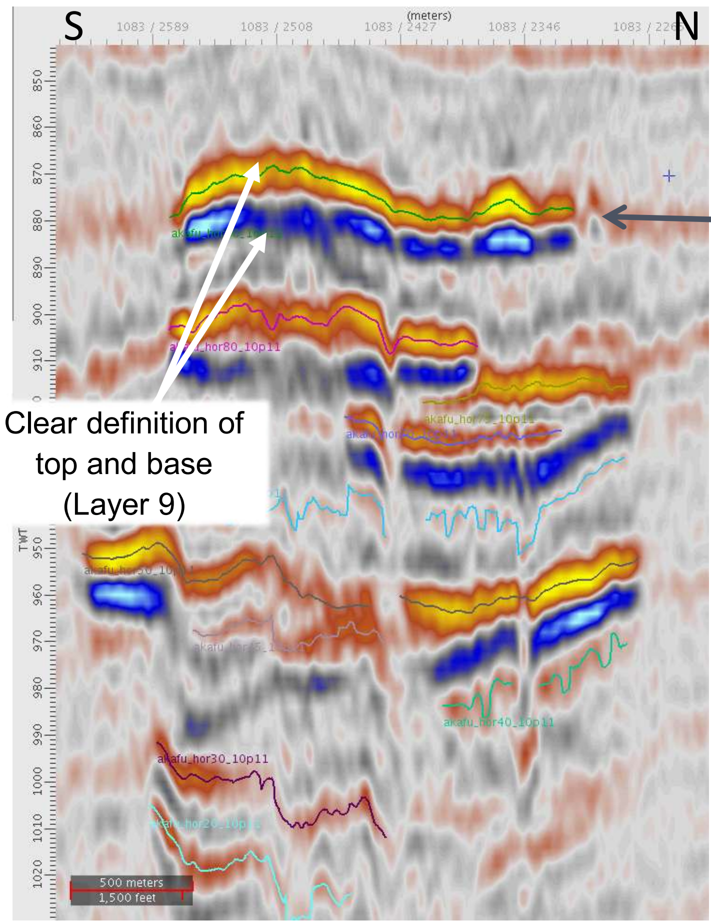


Fig. 14. from Landrø et al. (2019), IJGGC

How is this relevant to CO_2 storage?

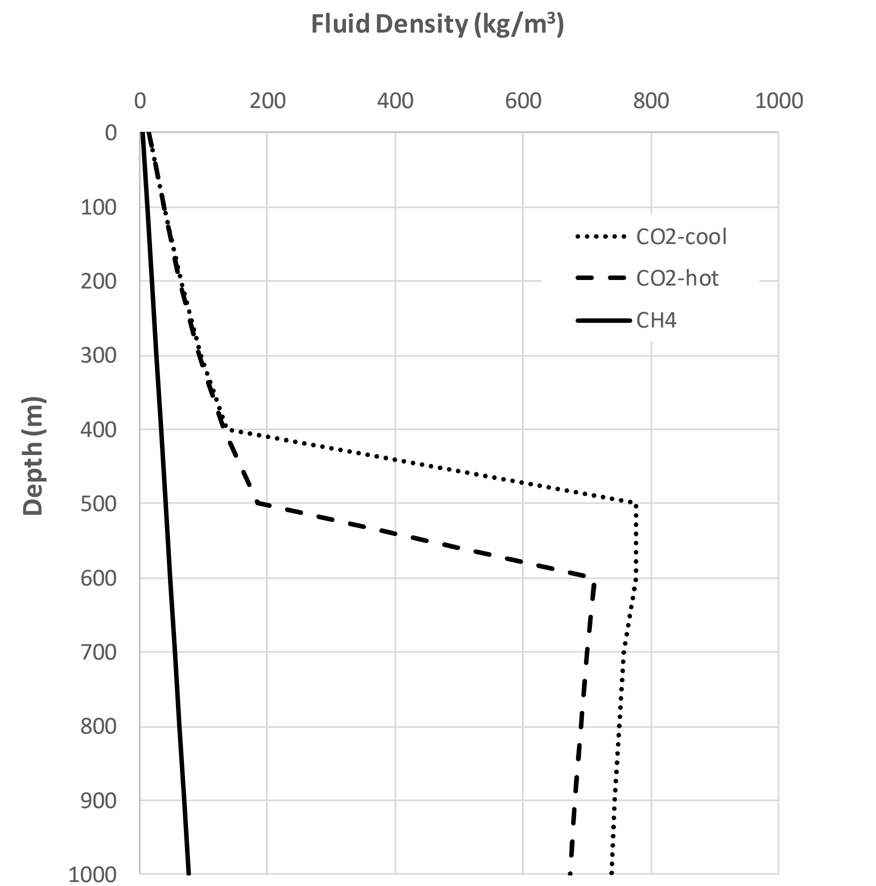
A CO_2 store is quite different from a large gas field because CO_2 is less buoyant and has a much lower column height



The top CO_2 layer at Sleipner is <20m thick which implies a buoyancy force of <130 kPa:

- about 1.3 atmospheres of pressure

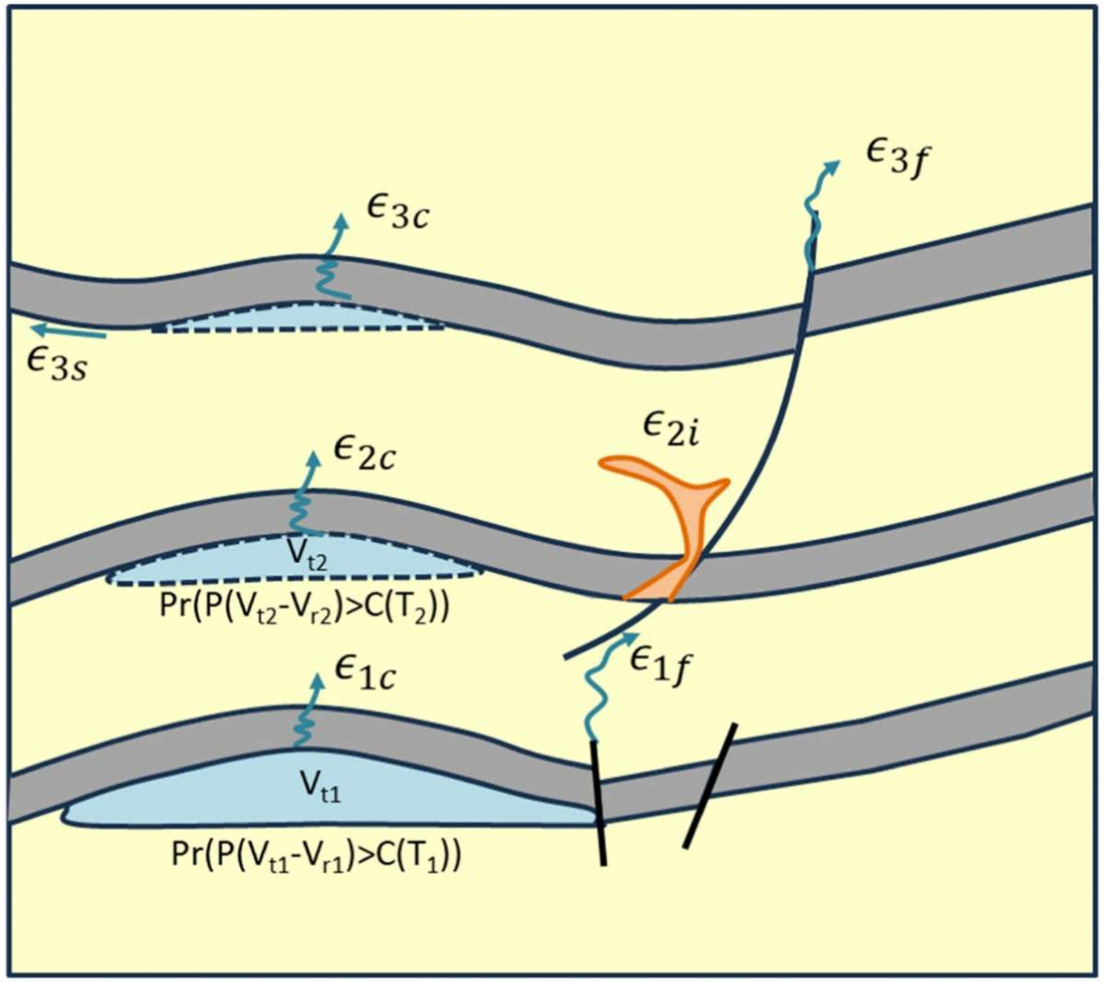
Example cross-section through the 2010 seismic amplitude data at Sleipner showing amplitude variations for the upper layers of the CO_2 plume.



Density profiles for CH_4 and CO_2 for typical conditions in the top 1000m sediment column in an offshore North Sea basin setting.

Invasion Percolation Modelling of CO_2 migration

We have proposed an **Invasion Percolation Markov Chain (IPMC)** approach to model CO_2 migration events (Callioli Santi et al., 2025, IJGGC).



Migration occurs when $P(V_{ti}-V_{ri}) > C(T_i)$

P = buoyancy pressure of the accumulation of $CO_{2;}$
t_i = permeable rock element, *i=1,…m*;
T_i = low permeability layer, *i=1, …m*;
V_{ti} is the volume of the non-wetting fluid in rock element $t_{i;}$
V_{ri} is the residual volume;
$C(T_i)$ is the threshold pressure of the low permeability layer T_i.

Probabilistic framework for assessing rock properties and migration events

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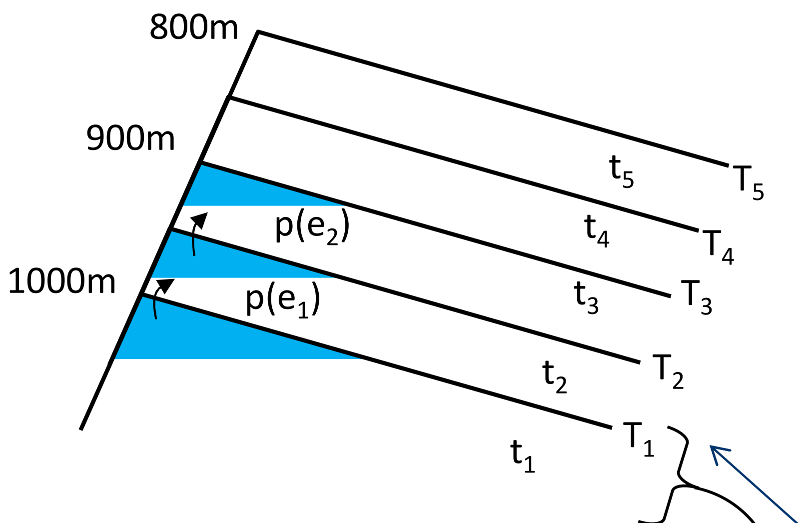
Simple example: IPMC for assessing CO_2 storage containment risks

Consider a simplified stack of storage units ($t_{1\text{-}5}$) separated by sealing layers ($T_{1\text{-}5}$) in a tilted fault block.



t_n and T_n comprise a rock-element pair, in which t is the porous unit and T is the sealing unit (each with a defined capillary threshold pressure distribution)

Callioli Santi et al. (2022)

Maximum CO_2 column heights with estimates for probability of migration

➢ All shales have the same gaussian distributions for threshold pressures

Layer	Depth to crest (m)	Pore Volume (m³)	Maximum column height(m)	Local migration probability	Joint (MC) Probability
t1	1000	5000000	50	8.00 %	8.00 %
t2	950	4000000	40	5.12 %	0.4096 %
t3	900	3200000	32	3.80 %	0.0156 %
t4	850	2560000	25.6	3.09 %	0.0005 %
t5	800	2048000	20.48	2.64 %	0.000013 %

Migration events always leave some CO_2 behind (residual and solubility trapping)

In a multi-barrier geological system, CO_2 migration and leakage faces a lot of resistance!

Helps determine what to monitor – i.e. focus on the immediate overburden layers

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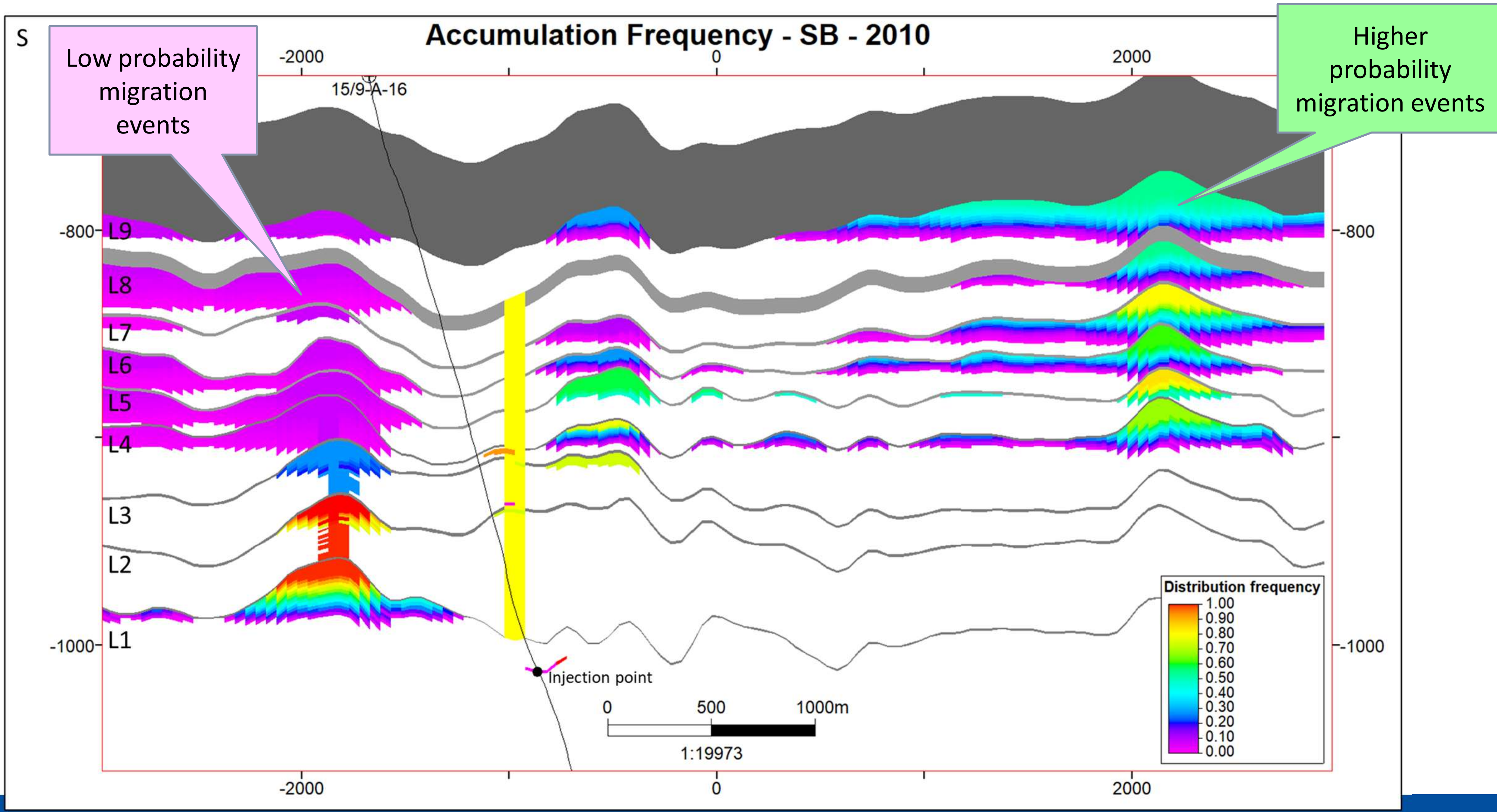
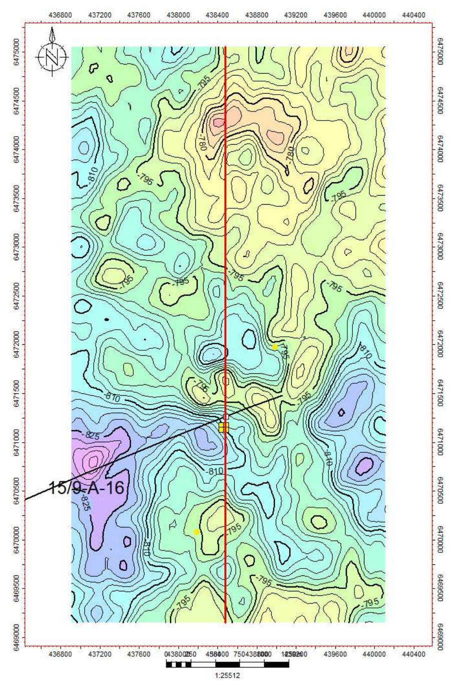
IPMC method applied to Sleipner

Accumulation frequency of CO_2 from the 500 runs in the shales with breaks scenario (SB)

Callioli Santi et al. 2025





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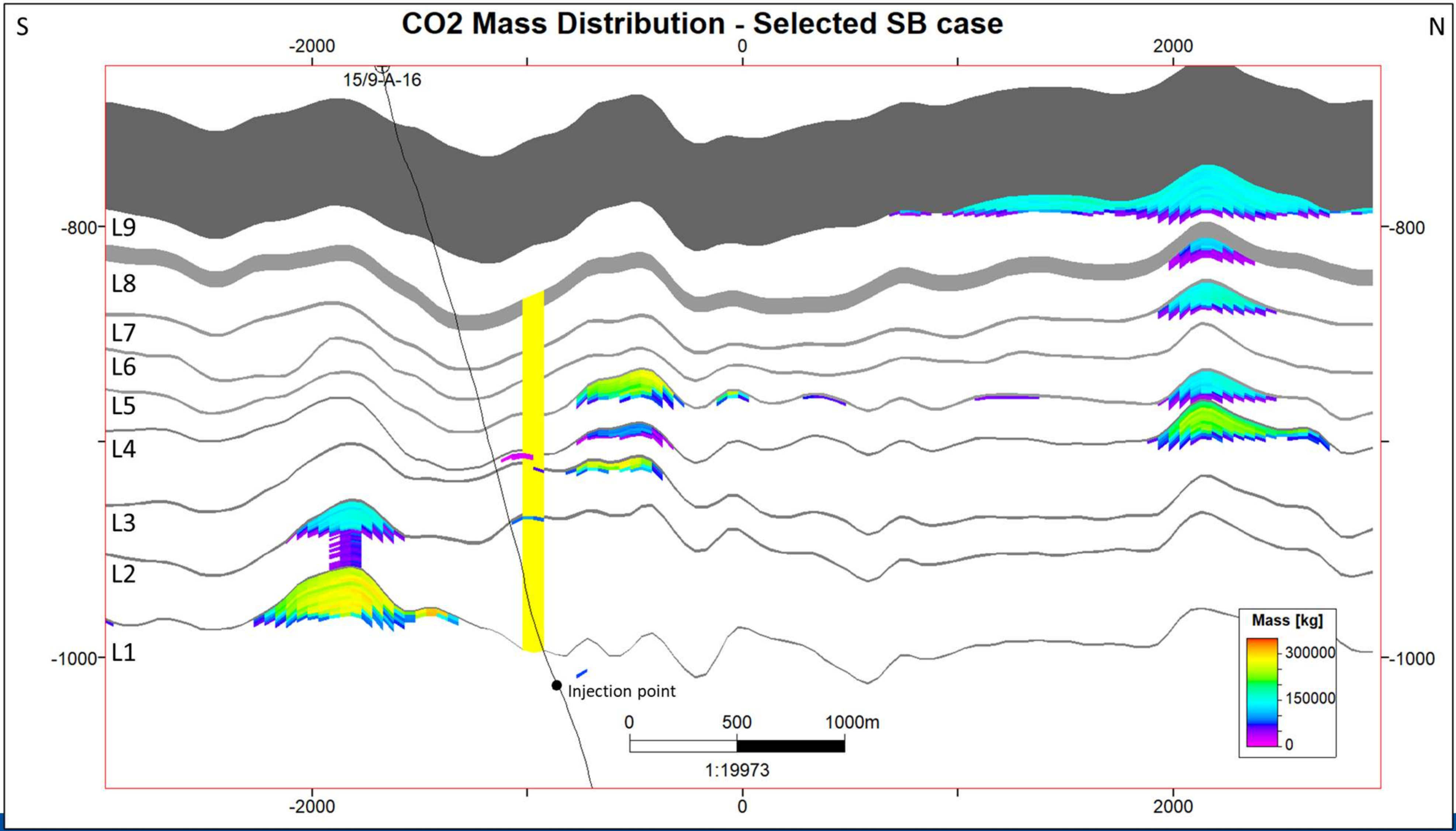
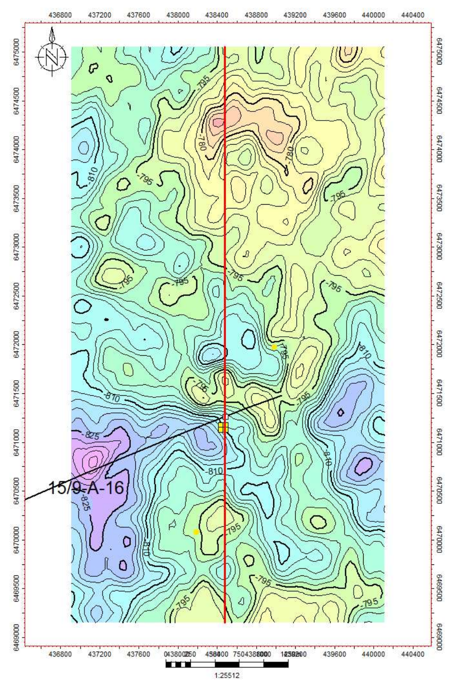
IPMC method applied to Sleipner

Mass distribution of CO_2 from the 500 runs in the shales with breaks scenario (SB)

Callioli Santi et al. 2025





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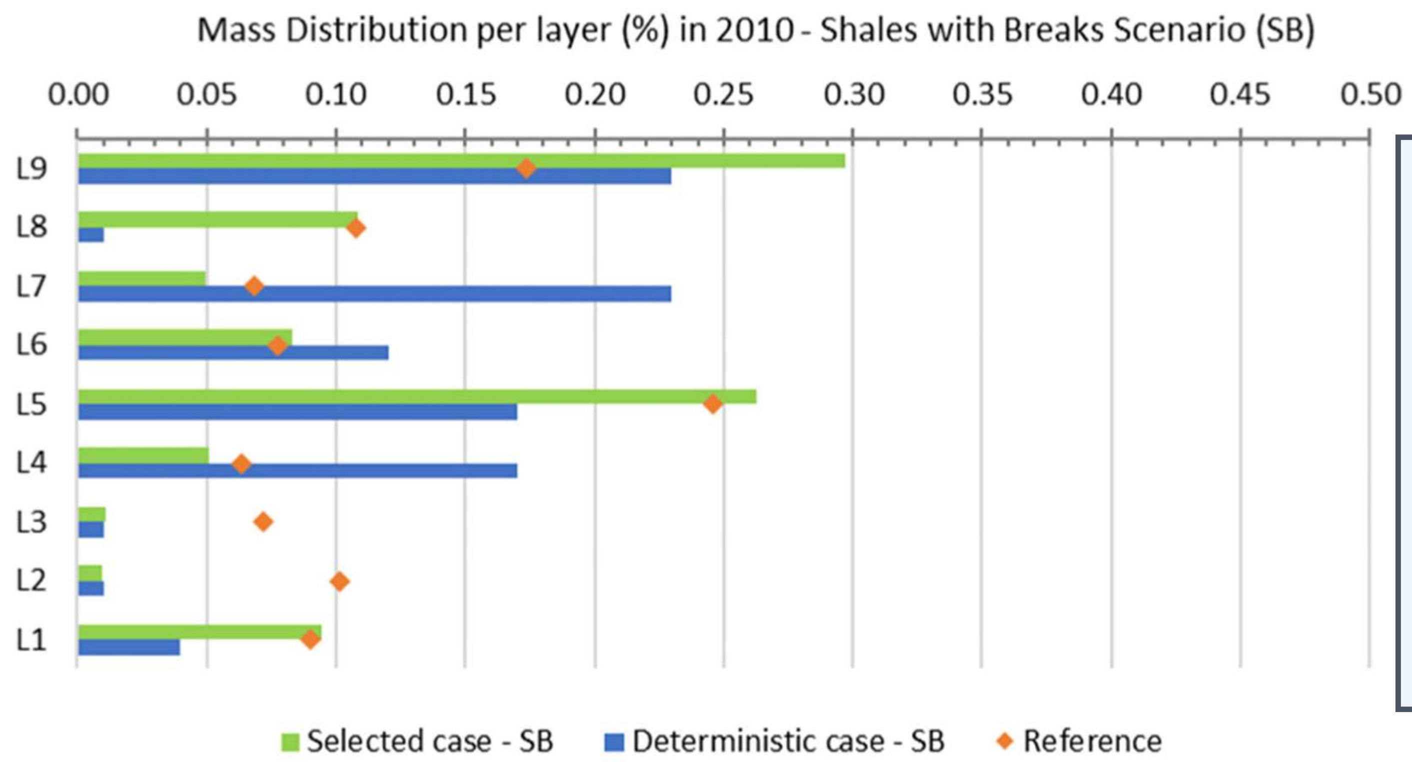
IPMC method applied to Sleipner

1. Study demonstrates that migration of CO_2 at Sleipner does follow a Markovian model
   - ➢ Probability of later migration events is highly dependent of the probability of preceding events.
2. Reveals the importance of vertical feeders and/or faults



- Reasonable overall forecast of the true mass distribution per layer
- Predicting this migration process is challenging due to the small and subtle heterogeneities (esp. feeders)
- Recent advances in developing hi-res velocity models using FWI can help improve the over predictability of the plume dynamics

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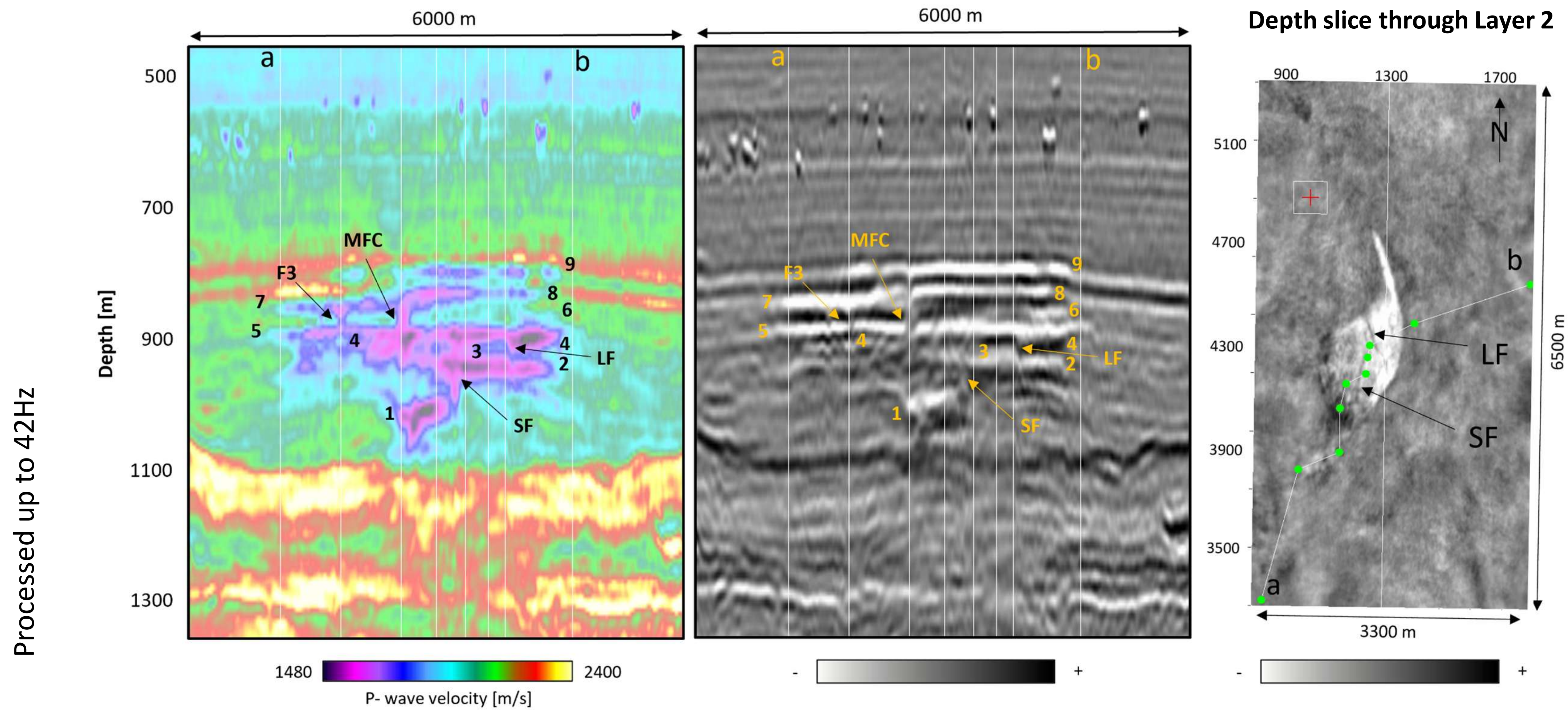
Learning from seismic data at Sleipner

Full-waveform inversion (FWI) of the 3D seismic data (here using 2010 marine-streamer acquisition) has allowed us to infer high-resolution 3D velocity models that reveal the nine layers of CO_2 and the vertical feeders (Ricardo Martinez et al. 2024, 2025)



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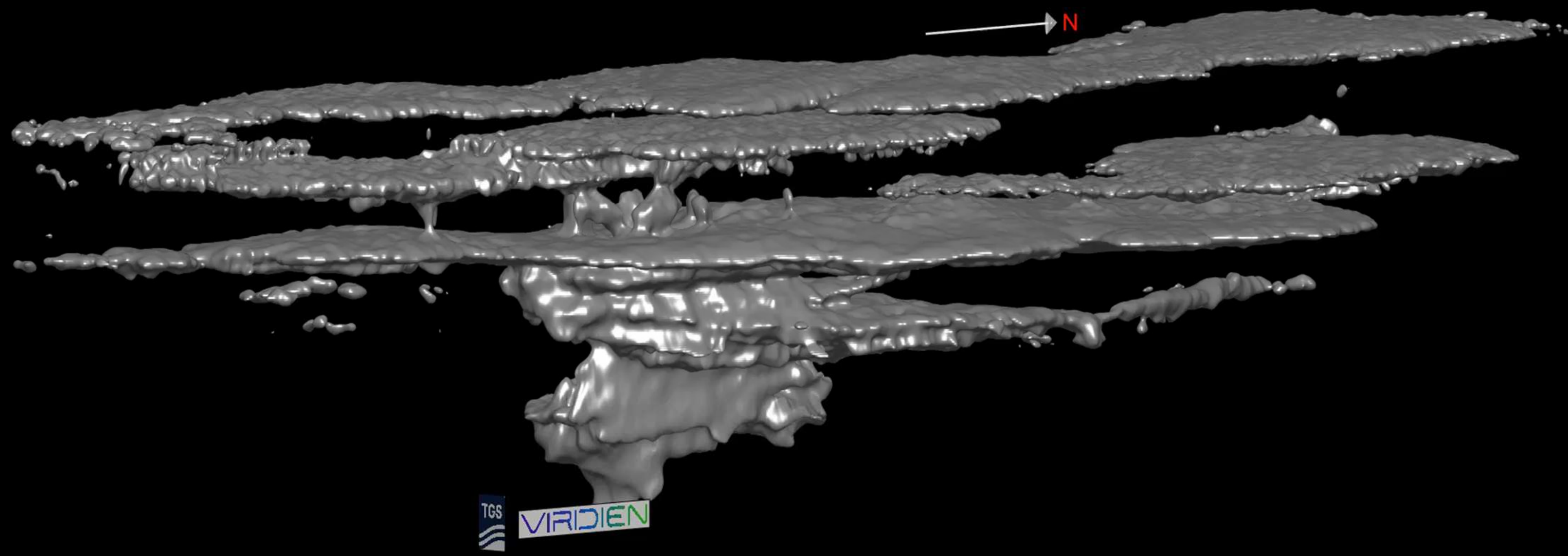
Latest FWI inversion of the CO_2 plume at Sleipner (OBN data, 2023)



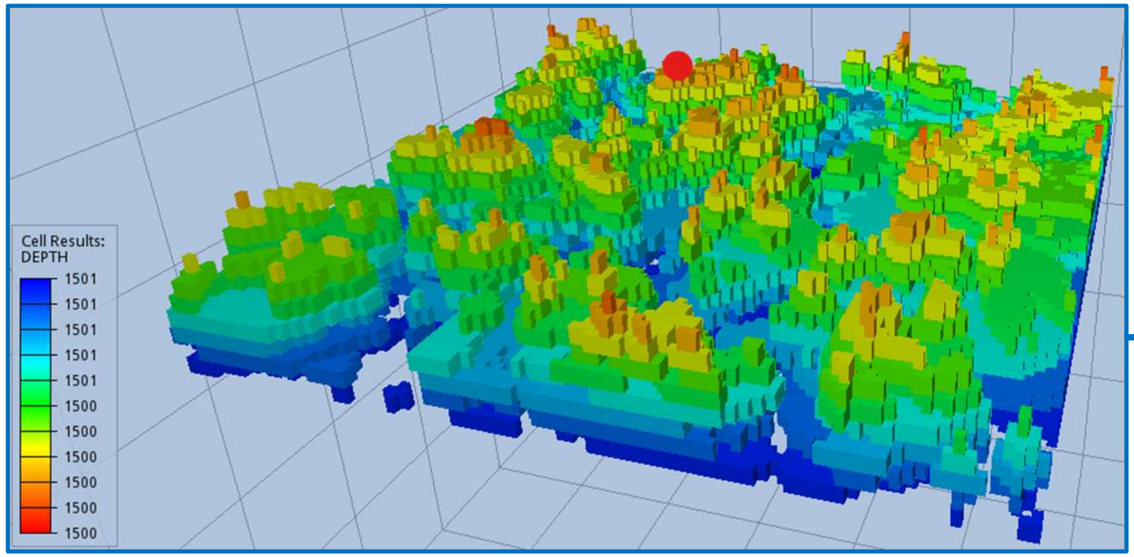
Iso-velocity model (1762.5 m/s) of the CO_2 plume at Sleipner 2023 - Martinez et al. 2025 (EAGE Annual)

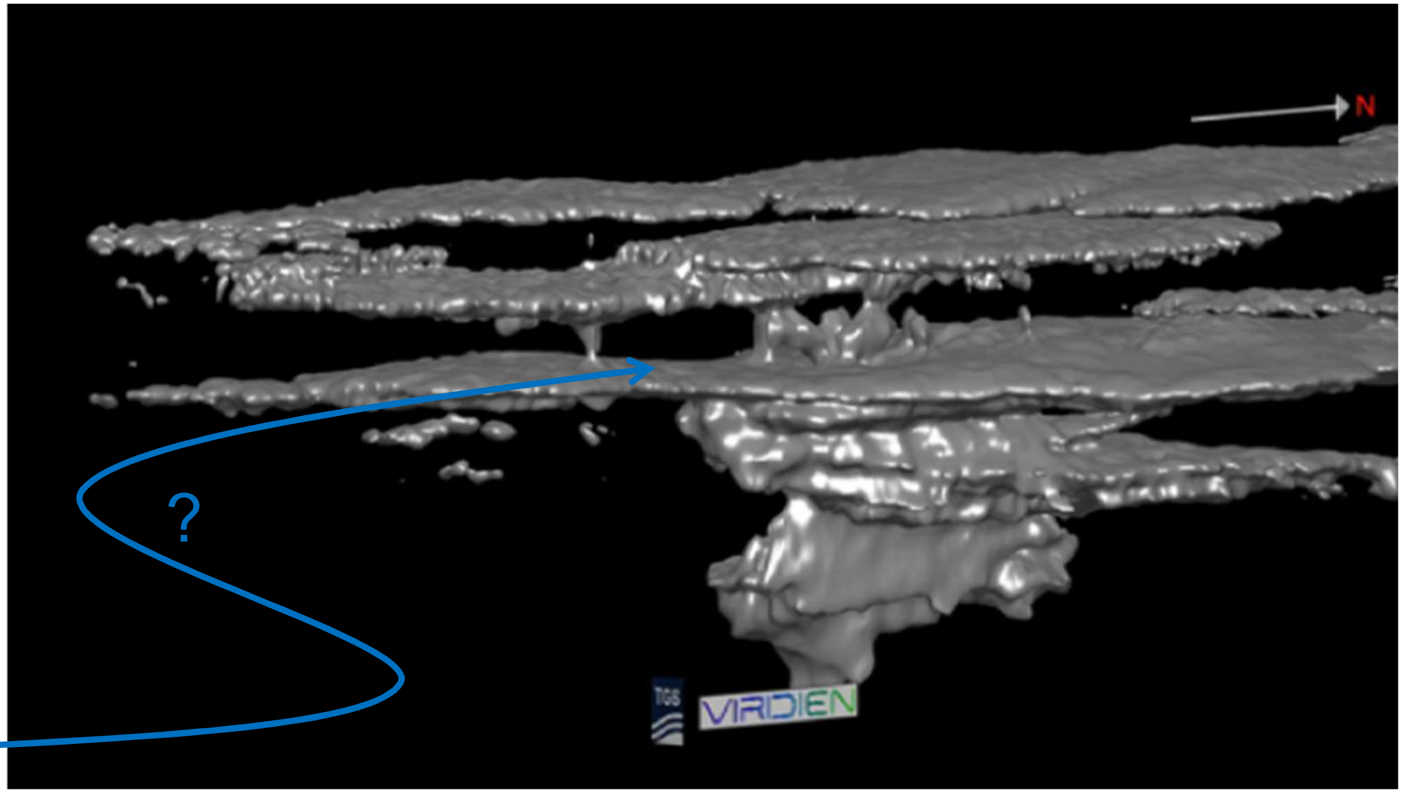
Derived from FWI analysis of the 2023 4-component OBN 3D seismic survey acquired by TGS and Viridien

Processed up to 70Hz

What is happening within the CO_2 plume at Sleipner?

1. What is the CO_2 saturation at the moment of breakthrough?
   - Hi-res simulation of a single sandstone layer (Poro-perm values from Sleipner)
   - Model dimensions: 10m x 10m x 1m
   - Only buoyancy-driven fluid forces
   - Mean CO_2 saturation at breakthrough: 14-16%
     - ➢ Depends on heterogeneity assumptions
   - Multiphase-flow software OPM-FLOW
   - Simulations by Mateja Macut (NTNU/SMILE)





CO_2 invaded cells at the moment of breakthrough.
Breakthrough is marked with a red dot.

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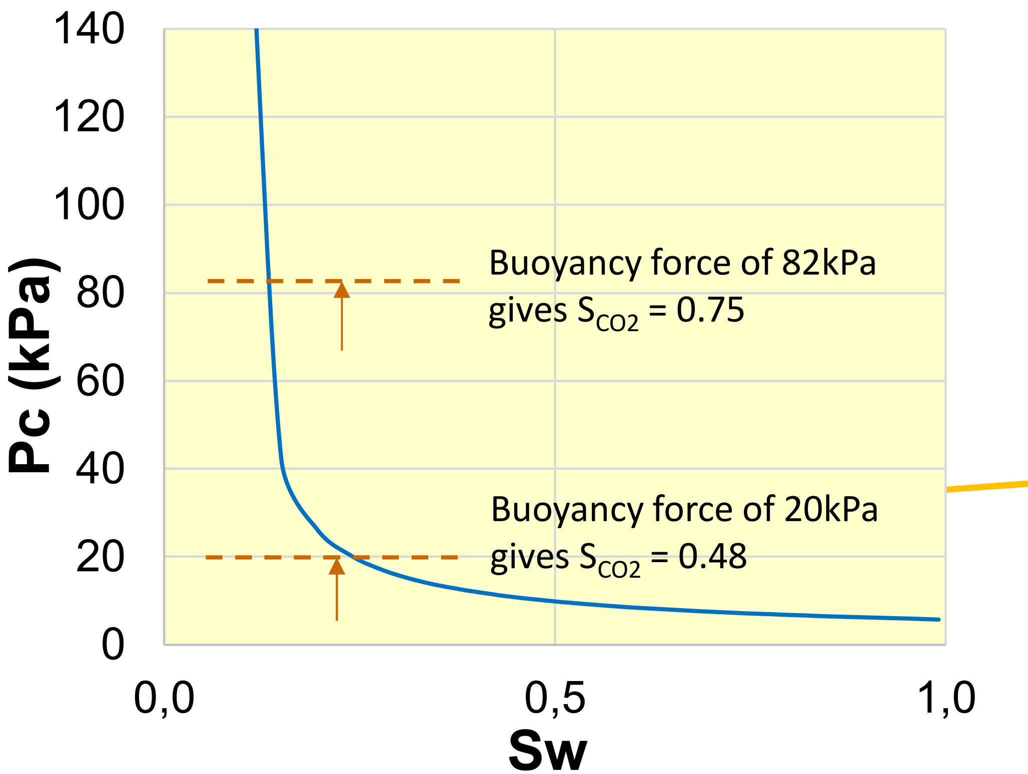
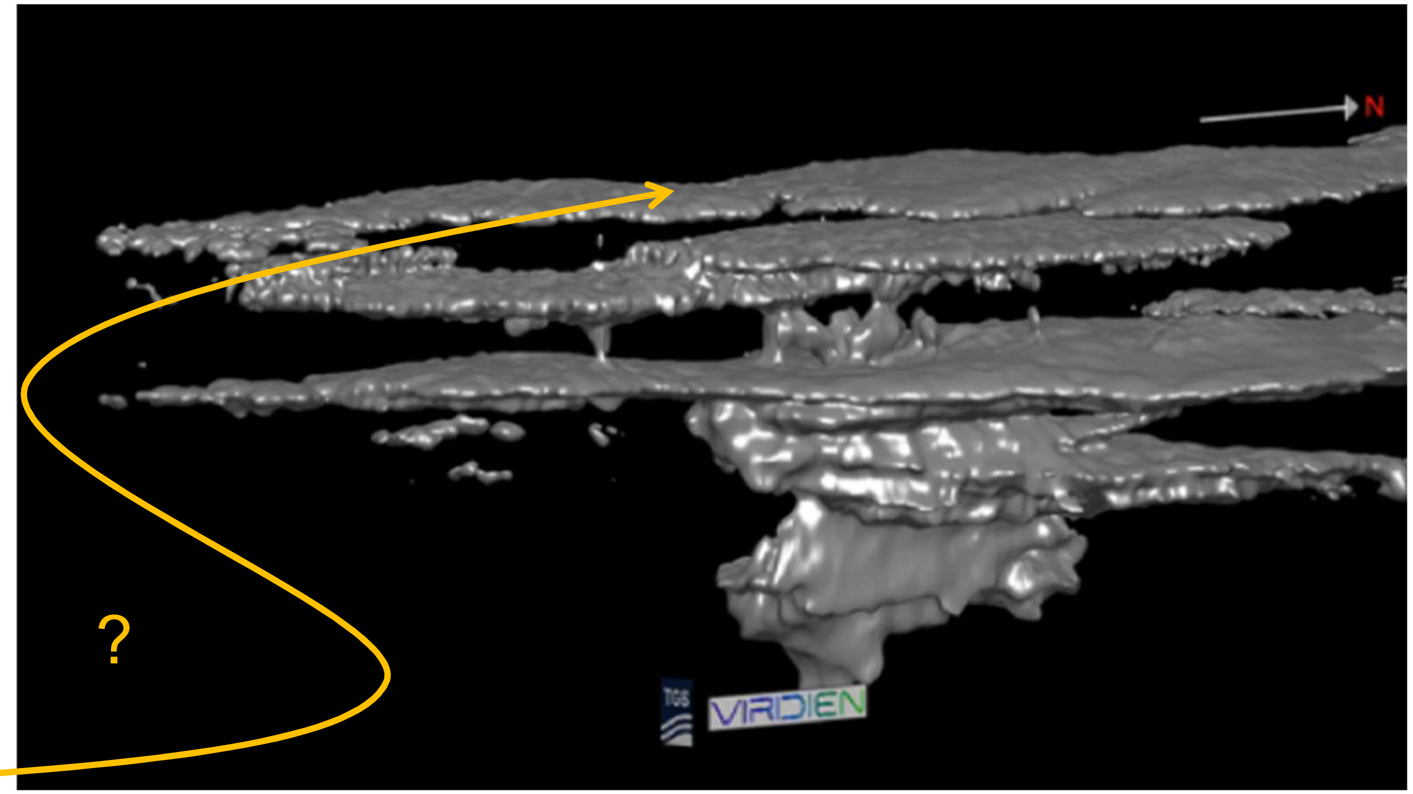
What is happening within the CO_2 plume at Sleipner?

2. What is the CO_2 saturation within the structural closures?
   - Expected saturations for different CO_2 column heights at Sleipner (gravity-capillary equilibrium):
     - 5m thick column has S_{CO2} = 48%
     - 20m thick column has S_{CO2} = 75%
     - CO_2 density assumed to be 600 kg/m^3
     - Ringrose et al. 2024 (GHGT17)

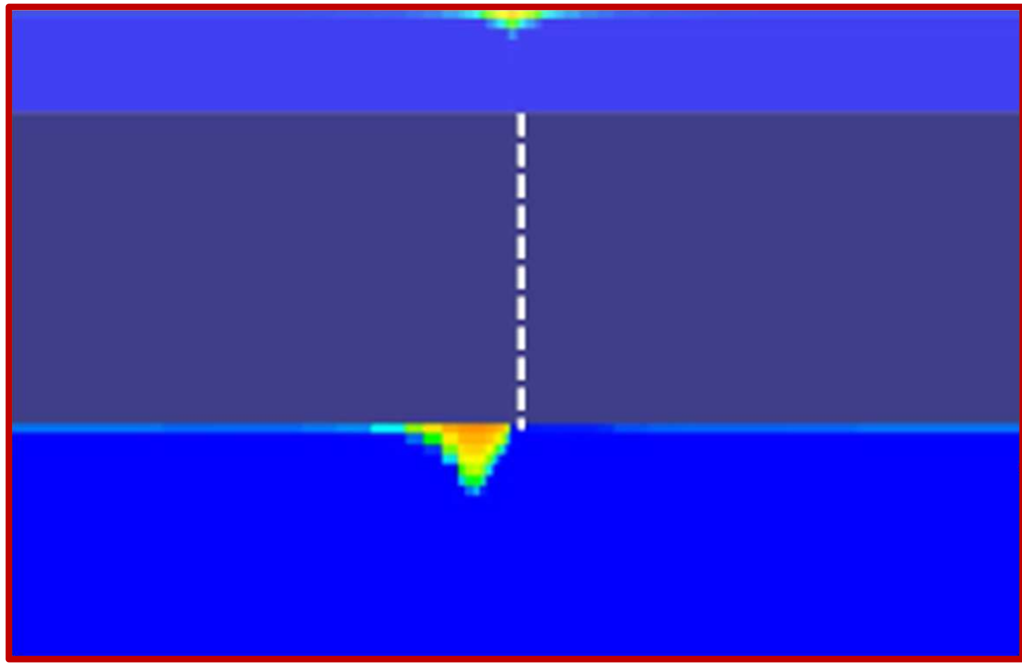


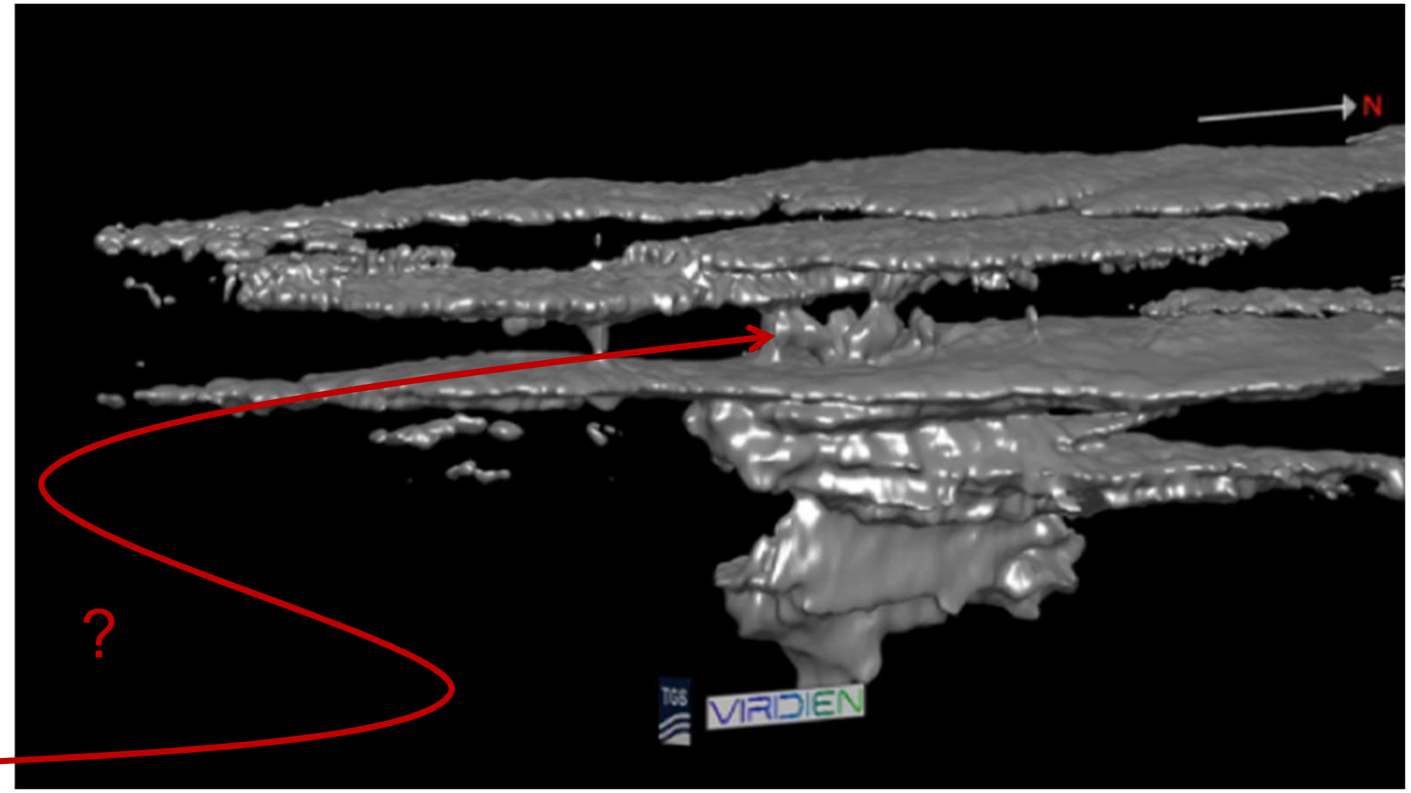


Capillary pressure function for Sleipner fluid and rock properties

What is happening within the CO_2 plume at Sleipner?

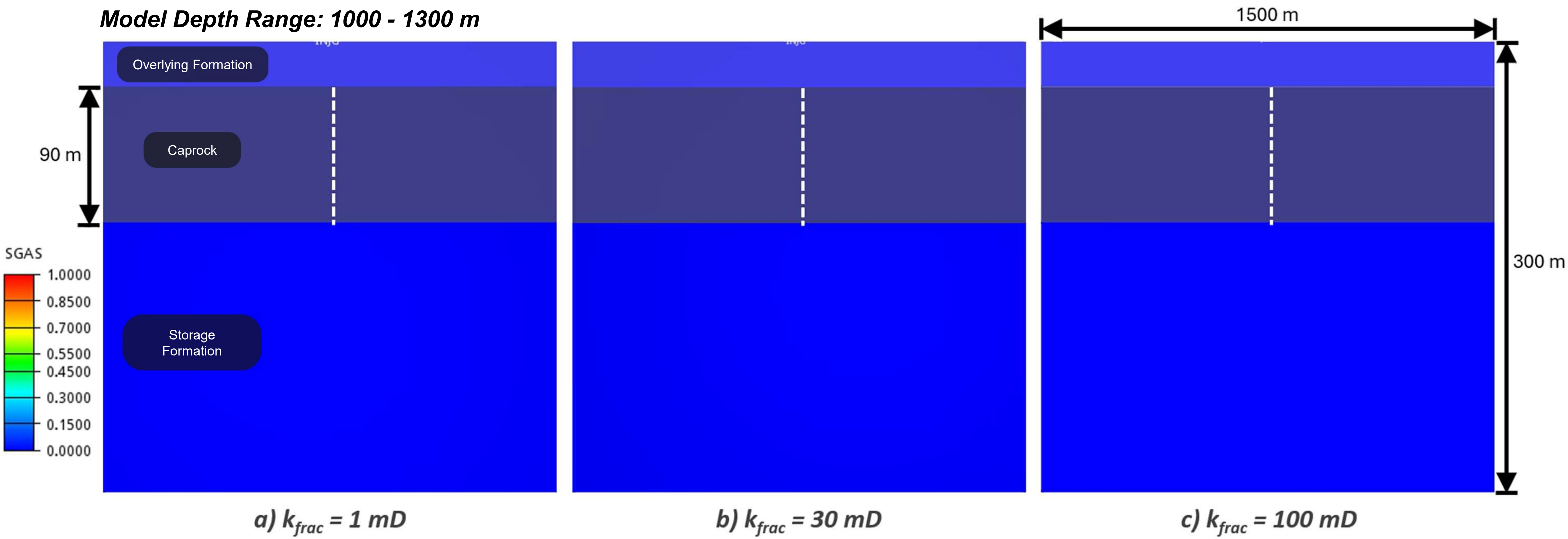
3. What are the conditions for migration through the shale layers?
   - Example simulations of buoyancy-driven flow through a 90m-thick shale
   - 'Leverett-J' type scaling of P_c functions
   - Sleipner-based rock/fluid properties
   - Multiphase-flow software PFLOTRAN
   - Simulations by Tae Kwon Yun (NTNU/SMILE)





Buoyancy-driven flow through a fracture in a 90m-thick shale

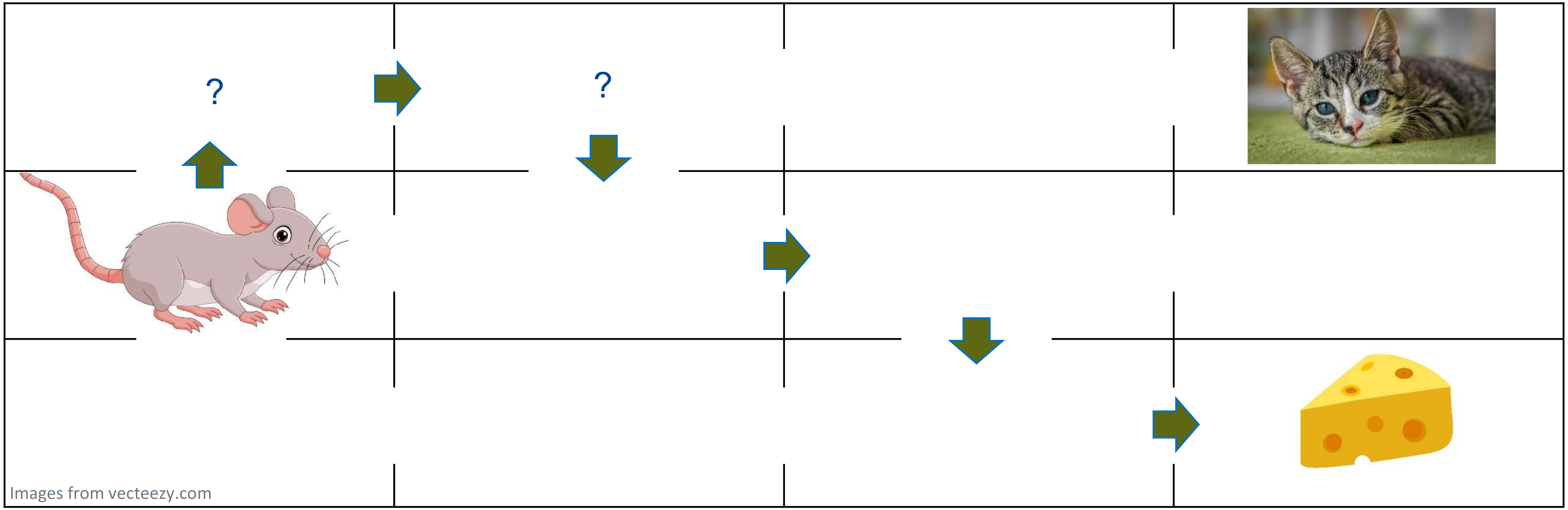
Buoyancy-driven flow for a fracture through a 90m-thick shale



- $scCO_2$ distribution for high permeability fracture in a 90m thick shale
- Sleipner-based rock & fluid properties with continuous injection for 2 years
- Simulations by Tae Kwon Yun using PFLOTRAN

Markov chains – a quick reminder

The mouse and cheese maze



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Multi-physics components of CO_2 trapping and migration

	CO_2 migration enablers		CO_2 migration resistors
✓	Buoyancy force	✓	Sealing units (capillary forces)
✓	Breaks in shales (depositional)	✓	Mass loss (residual trapping)
✓	Fractures in shales (geomechanical)	✓	Mass loss (dissolution)
✓	Hydro-fracture (applied pressure)	?	Shale creep (mechanical sealing)
?	Thermal fractures (cold CO_2 injection)	?	Carbonate precipitation (chemical sealing)
?	Wellbore migration (damage zone or corrosion)	✓	Pressure management (prudent operators)
?	Earthquakes (change in stress field)	✓	Monitoring (prudent operators)
	Other cats … 		Other bits of cheese … 

✓ = reasonably good models & data

? = needs more work (models & data)

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Rock mechanics and CO_2 storage

Projects need to assess:

- Elastic response to pressure increase
- Likelihood of induced fractures or faults
- Thermal effects during CO_2 injection (Grande et al. 2024, IJGGC)

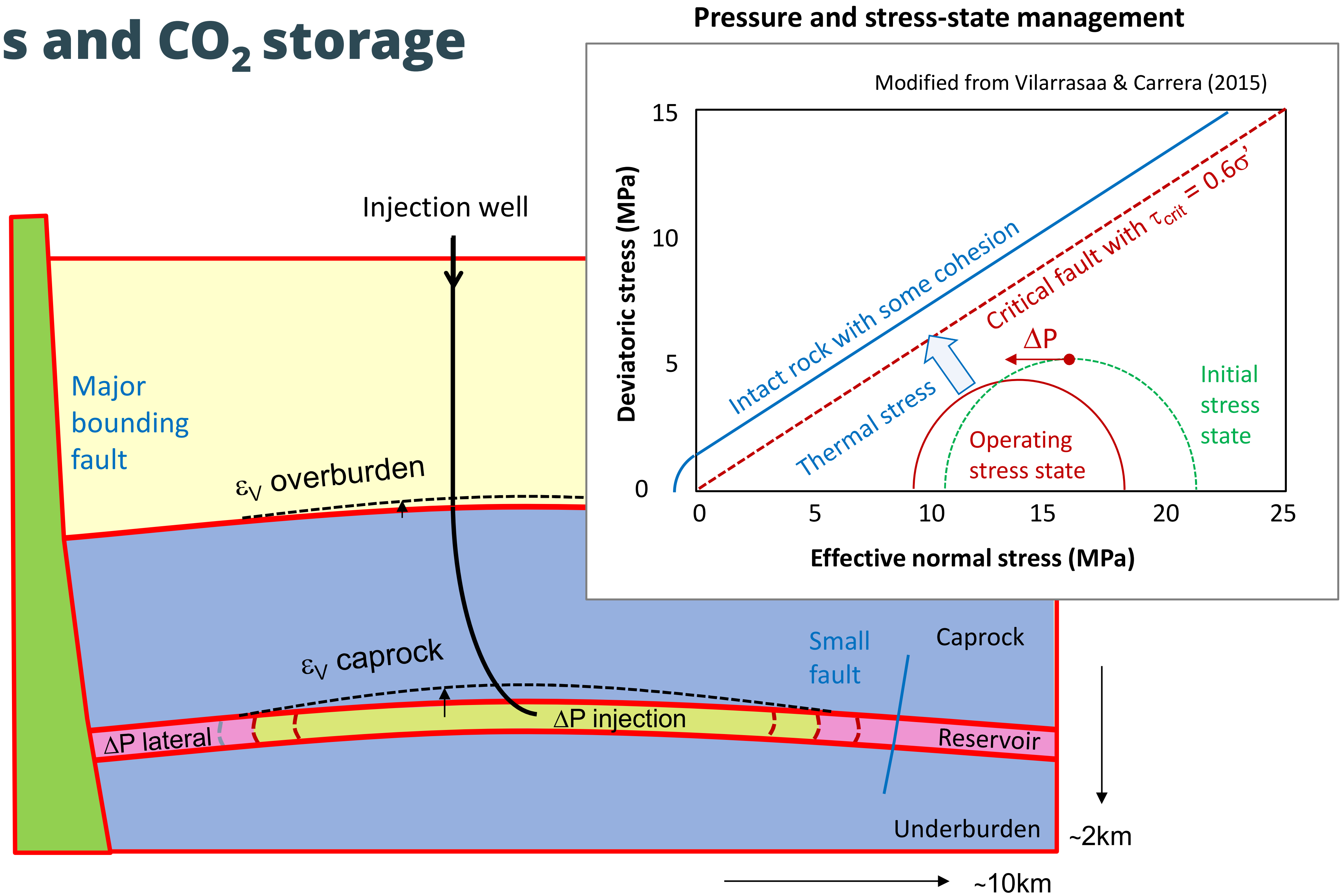


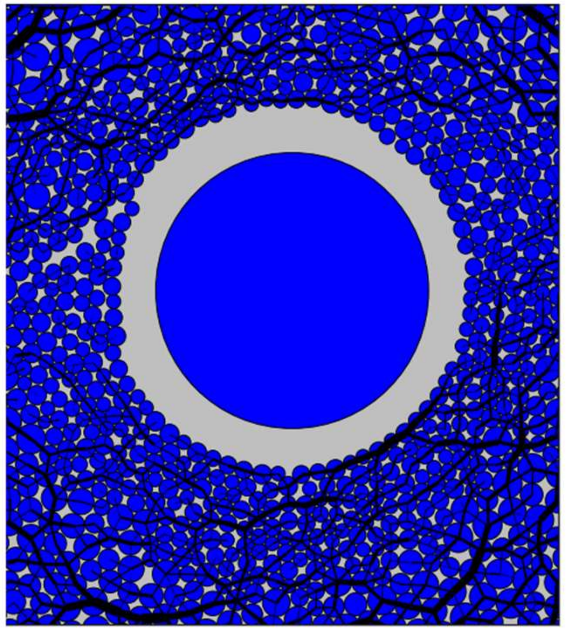
Illustration of rock strain response to elevated injection pressure in a reservoir unit. ΔP = change in fluid pressure; ε_v = vertical component of rock strain.

Shale creep

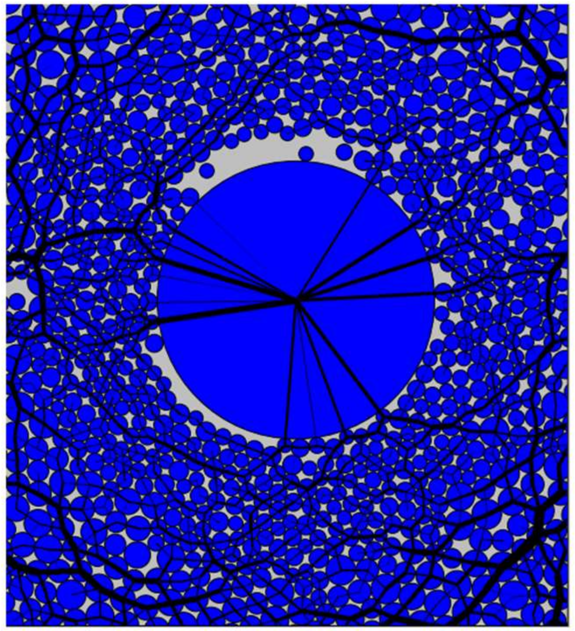
- Shale creep is likely beneficial for improved sealing due to gradual closing of natural/man-induced fractures in shales (Fjær et al. 2016).
- In a study of the geochemical controls on the shale creep process, Cerasi et al. (2017) found that increased creep behaviour was observed when a laboratory shale was exposed to low-pH brine solutions (caused by CO_2) as compared to neutral pH brines.

Snapshots of DEM model of creeping shales around a wellbore-rock gap
(from Fjær et al. 2016)

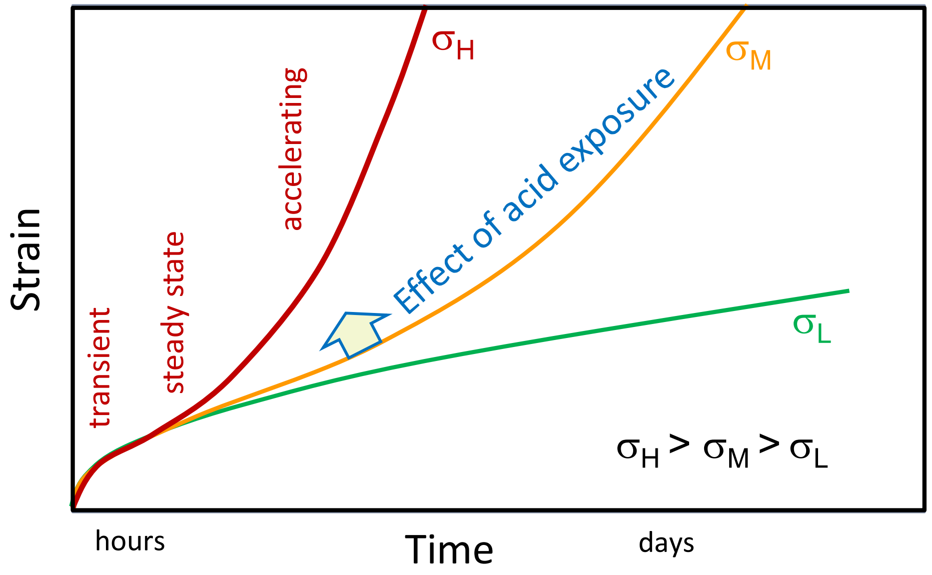
(a) t = 0 days



(e) t = 1000 days



Influence of applied stress on shale creep
(redrawn from Cerasi et al. 2017)



Carbonate precipitation?

- Open fractures exposed to CO_2-brine fluid mixtures will also tend to be the loci for the precipitation of carbonate cements – which gradually seal up the fractures of concern.
- Studies of these processes in the near-wellbore environment indicate that even where mechanical or thermal fractures might occur, the carbonate precipitation process will tend to counteract the geomechanical risks.

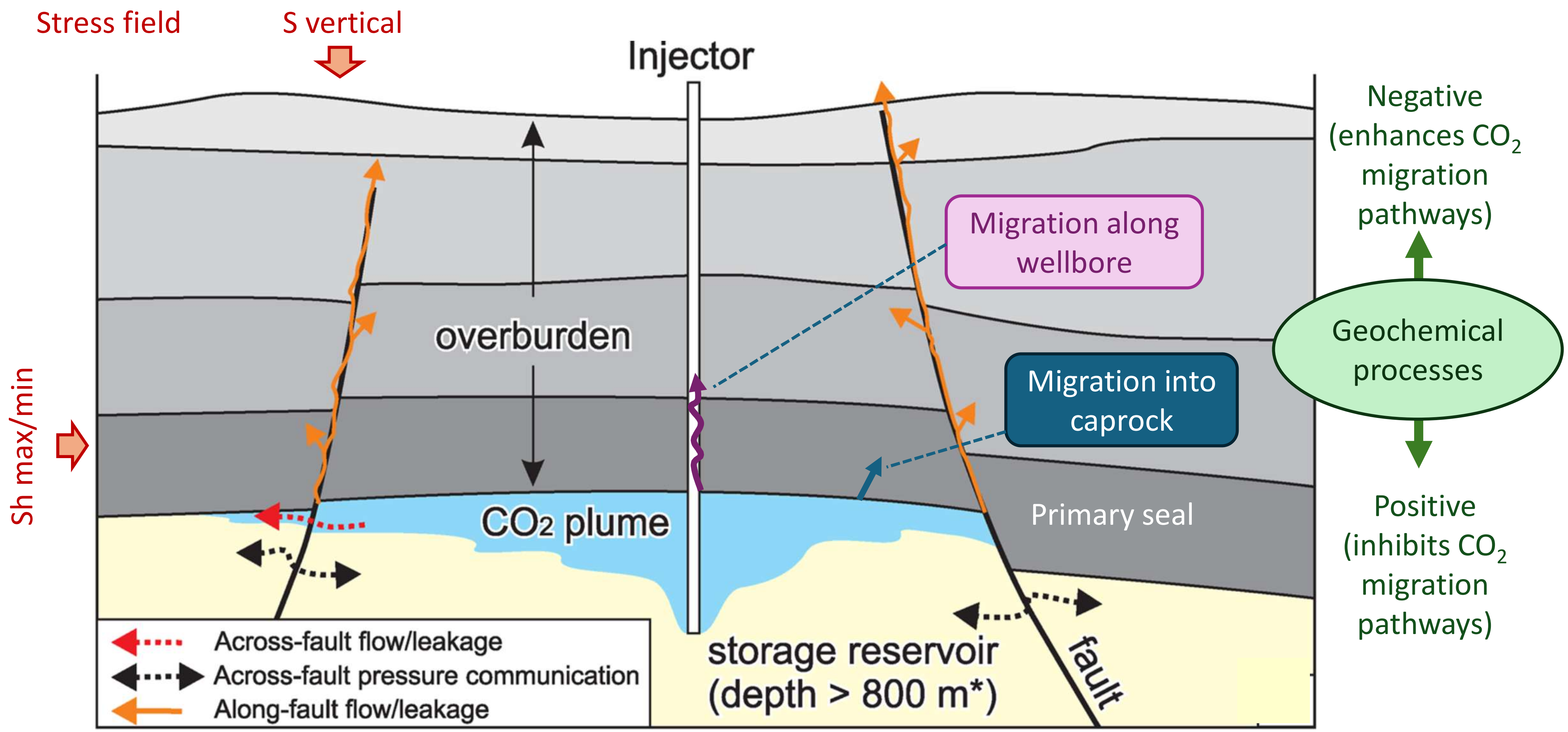
- Wolterbeek et al. (2016) concluded that:
  - ‘a well exposed to CO_2 may actually be more resilient to leakage pathway formation, compared to a CO_2-free well exposed to the same changes in downhole temperature and stress state’
  - ‘more or less complete mechanical healing can occur on timescales of the order of months’

However, we know relatively little about how the geomechanical properties of faults/fractures in caprocks might be affected by geochemical reactions over human/geological timescales.

Fractured limestones filled with carbonate cement, Escurets peak, French Pyrenees (analogue to Lacq-Rousse CO_2 storage units in the Aquitaine basin)

Overview of containment risks and processes

Sketch of fault-related migration pathways, wellbore migration pathways, and coupled geomechanical and geochemical processes. Figure modified from Wu et al. (2021)



Could faults and wells leak CO_2 sometime in the future?

- This is a hard question to answer – but natural analogues can help
- There are many natural stores of CO_2 in volcanically-active regions of the world:
    - Bravo Dome in New Mexico contains 1.6 Gigatons of CO_2 which has been there for approximately 1.3 million years
      (Sathaye et al. 2014. PNAS)
- Humans (especially the Romans!) have been living alongside natural CO_2 vents for 1000's of years
- Study of a 400-thousand-year-old leaky fault in a CO_2 volcanic region (Paradox Basin Utah) shows a maximum leakage rate of around 870 t/yr - at the Crystal Geyser tourist spot!
  (Burnside et al. 2013)

So, the most leaky fault on Earth (in a volcanic region) is leaking CO_2 at a rate equivalent to the annual emissions of 100 Norwegians ... or 60 Americans!

"Jenn couldn't resist playing in the geyser. They don't let you do this in Yellowstone!"
Travel blog from www.rvoutoftheratrace.com/My%20Albums/Utah%20Sep%202008/slides/Jenn%20playing%20in%20Crystal%20Geyser.html

Conclusions

1. The earth system has a strong tendency to absorb / retain / hold-back CO_2 injected into the subsurface
2. Invasion Percolation Markov Chains are a good & validated way of estimating migration pathways / risks
3. This 'sequential multi-physics' approach <u>should be applied to legacy-well risk analysis</u>
4. Geochemical processes mainly have a positive (inhibiting) effect as they interact with geomechanically controlled potential leakage pathways
5. But there are many remaining challenges in understanding these coupled processes, such as timescales:
   - Geomechanical responses typically operate over minutes to days
   - Geochemical processes operate over periods of months to 100's years

Ongoing studies to understand coupled processes (SMILE project) and natural tectonic CO_2 degassing in the North Atlantic between Iceland and the Norwegian Continental Shelf (NTNU CGF)

Geothermal energy, Reykjanes, Iceland

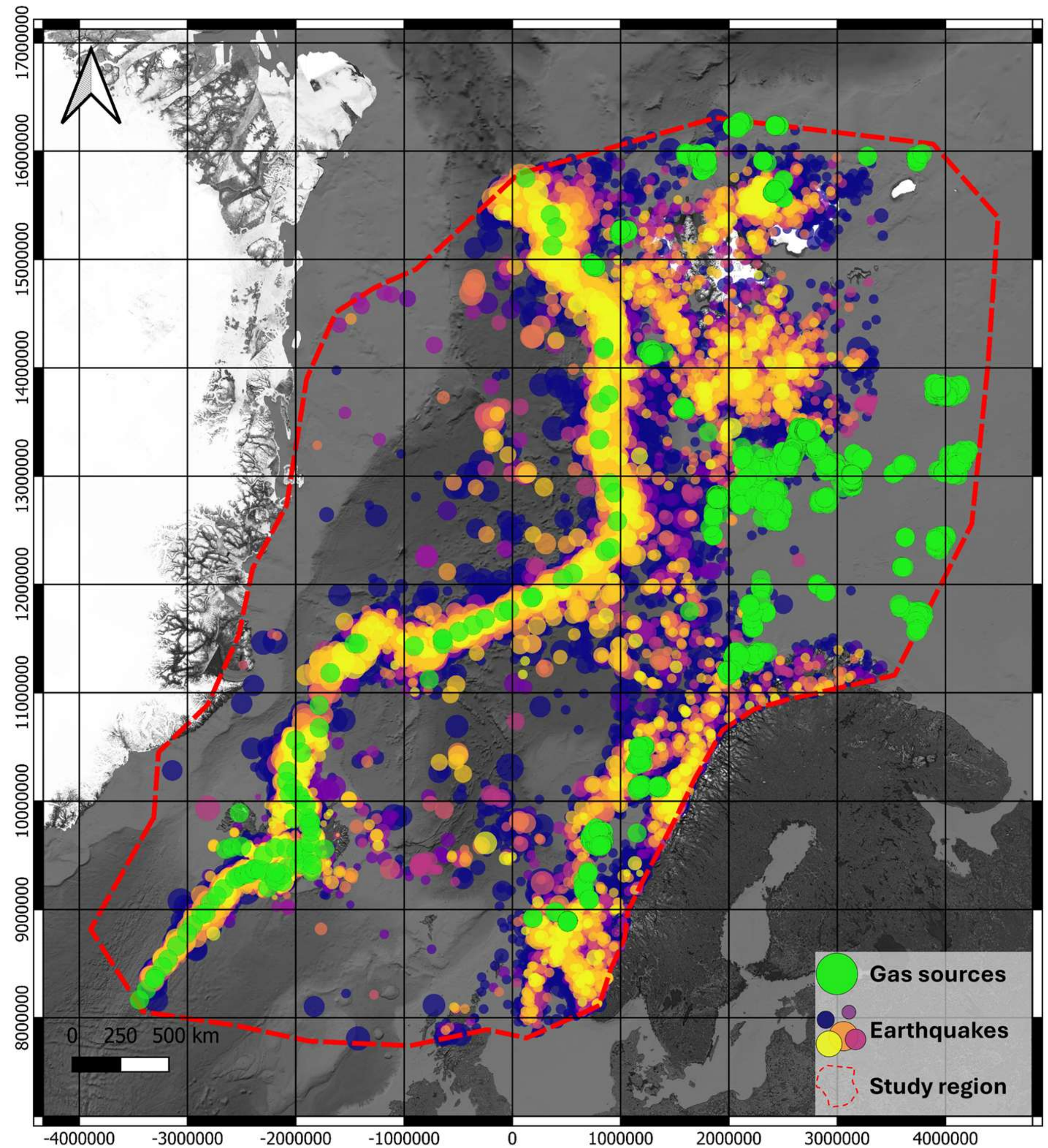
Tectonic degassing in the North Atlantic region

Ongoing work by Chloé Delbet (NTNU, CGF):

- ➢ Map of compiled natural CO_2 fluxes compared with seismicity in the region

Context:

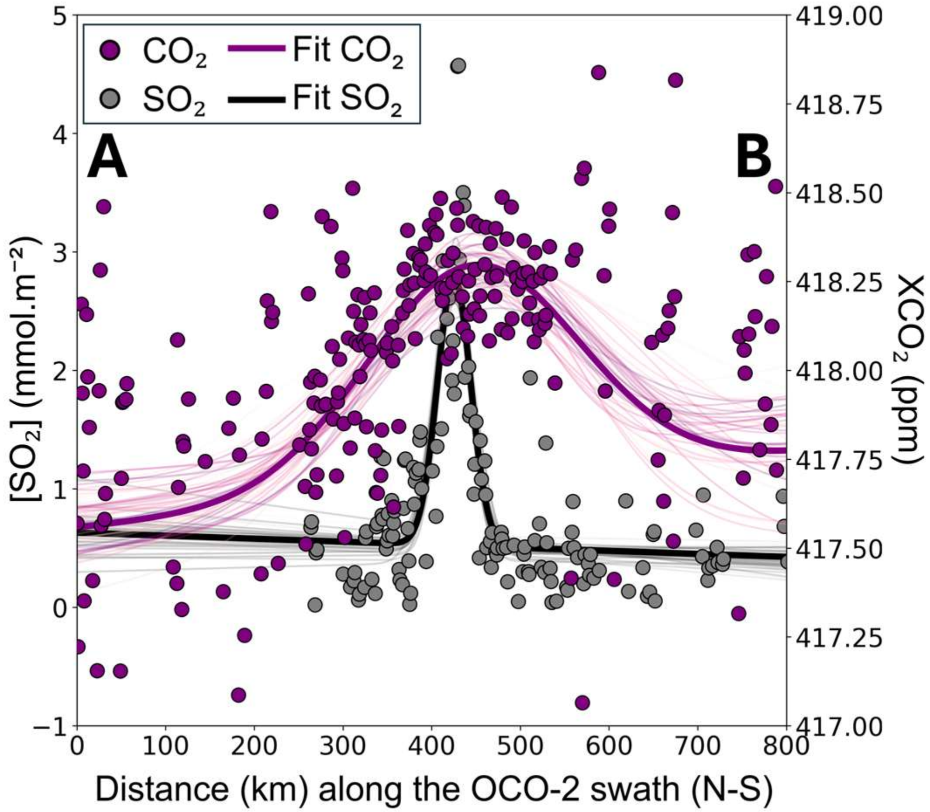
- Roughly 300 Mt/a of CO_2 are naturally emitted along active tectonic belts
- The correlation of natural CO_2 fluxes with tectonics serves as a valuable basis for assessing the potential for leakage from CCS sites and migration of CO_2 over geological timescales.

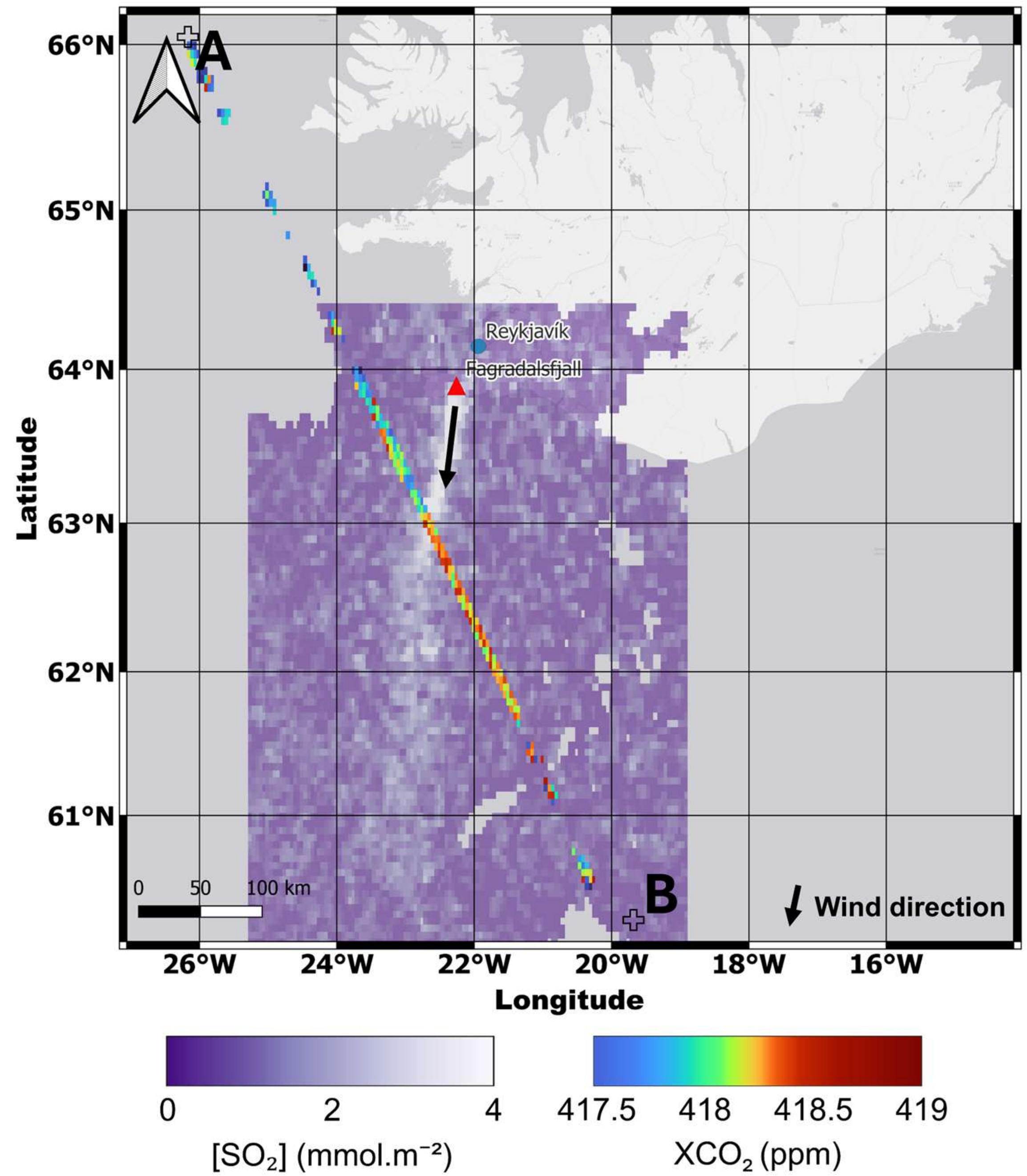


Satellite detection of volcanic CO_2 over Iceland

Delbet, C. and Ringrose, P., 2025, EAGE GET Conference

Co-located satellite detections, showing anomalies of 0.6 - 1 ppm (CO_2) and 2-4 mmol.m (SO_2) along the OCO-2 swath detected on May 4th, 2021 (Fagradalsfjall eruption).





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